

# Influence of surface abrasion on creep and shrinkage of railway prestressed concrete sleepers

Li, Dan; Ngamkhanong, Chayut; Kaewunruen, Sakdirat

DOI:

[10.1088/1757-899X/245/3/032040](https://doi.org/10.1088/1757-899X/245/3/032040)

License:

Creative Commons: Attribution (CC BY)

*Document Version*

Peer reviewed version

*Citation for published version (Harvard):*

Li, D, Ngamkhanong, C & Kaewunruen, S 2017, Influence of surface abrasion on creep and shrinkage of railway prestressed concrete sleepers. in *IOP Conference Series: Materials Science and Engineering: Session I - Construction Management and Engineering, Construction Materials, Geotechnics, Hydromechanics, Structural Engineering*. vol. 245, 032040, IOP Conference Series:, vol. 245, IOP Publishing Ltd., pp. 1-10, World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium, Prague, Czech Republic, 12/06/17. <https://doi.org/10.1088/1757-899X/245/3/032040>

[Link to publication on Research at Birmingham portal](#)

## General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

## Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

# Influence of surface abrasion on creep and shrinkage of railway prestressed concrete sleepers

Dan LI <sup>1</sup>, Chayut NGAMKHANONG <sup>1</sup>, Sakdirat KAEWUNRUEN <sup>1,2</sup>

<sup>1</sup> Department of Civil Engineering, The University of Birmingham, U.K.

<sup>2</sup> Birmingham Centre for Railway Research and Education, The University of Birmingham, U.K

E-mail: DXL561@student.bham.ac.uk

**Abstract.** Ballasted railway track is very suitable for heavy-rail networks because of its many superior advantages in design, construction, short- and long-term maintenance, sustainability, and life-cycle cost. The sleeper, which supports rail and distributes loads from rail to ballast, is a very important component of rail track system. Prestressed concrete is very popular used in manufacturing sleepers. Therefore, improved knowledge about design techniques for prestressed concrete (PC) sleepers has been developed. However, the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers. Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of abrasions in concrete sleepers. This paper presents a comparative investigation using a variety of methods to evaluate creep and shrinkage effects in railway prestressed concrete sleepers. The outcome of this study will improve the material design, which is very critical to the durability of railway track components.

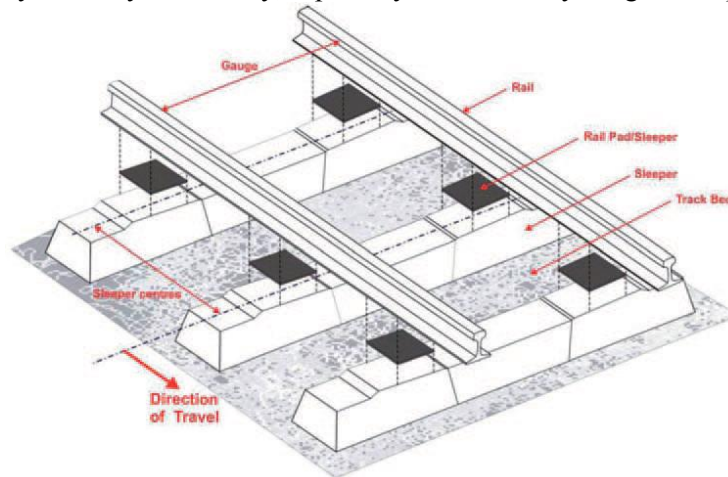
**Keywords:** prestressed concrete, sleepers, crossties, creep, shrinkage

## 1. Introduction

The railway has been developed for decades and it's believed that the safest transportation system for transporting passengers and heavy haul. Two main components of rail track consist of superstructure and substructure. The superstructure contains rails, rail pad, fastening system, and sleepers. The ballast, sub-ballast (or capping layer) and subgrade form the substructure. The structure of typical ballasted rail track is shown in Figure 1. In superstructure of rail track, the sleepers distribute axle loads to substructure [1]. The sleepers can be manufactured using timber, concrete, steel or other engineered materials [2]. The main functions of sleepers are:

- to support rails and maintain the rail gauge
- to transfer and distribute load from rail to substructure
- to provide insulation between parallel rails

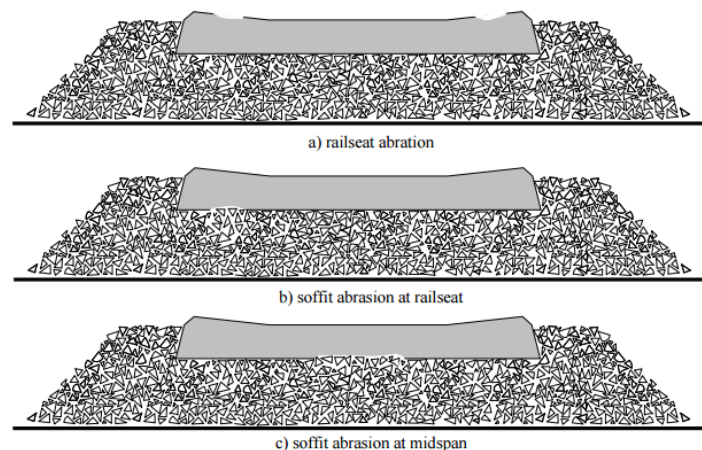
Prestressed concrete sleepers have been developed over 50 years and it is believed the most commonly used type of sleepers [3]. They have longer life cycle and lower maintenance costs in economic and technical aspects than reinforced concrete and concrete sleepers. Prestressed concrete sleepers provide high carrying capacity, stability, and safety, especially used in heavy freight transportation system [3].



**Figure 1:** Typical ballasted railway track component [1]

Durability and long-term behaviours of railway prestressed concrete sleepers depend largely on their creep and shrinkage response. Many investigators have proposed various material models to predict creep and shrinkage but those were mostly based on general reinforced concrete concept. The popular uses of prestressed concrete in long span bridges, stadiums, silos and confined nuclear power plants have led to a concern of practitioners whether those predictive models could be realistically applied to prestressed concrete. Due to high initial elastic shortening in prestressed concrete, the creep and shrinkage effects should be critically re-evaluated in flexural members.

In reality, the ballast is tamped by dynamic action at the railseat areas. Therefore, the bottom of sleepers (or called 'soffits') may experience the aggressive abrasive force, wearing out the materials in the region [4-6]. Most of the previous work revealed the dynamic behaviours, but long-term behaviours of prestressed concrete sleepers with abrasion were not fully investigated, especially when the sleepers are deteriorated by excessive wears [7-11]. The typical wears of prestressed concrete sleepers are shown in Figure 2.



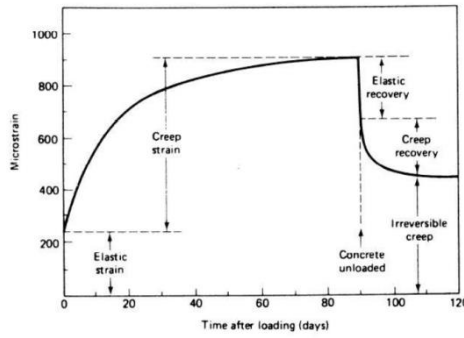
**Figure 2:** Typical wears of prestressed concrete sleepers

This study will investigate methods to evaluate creep and shrinkage effects in railway prestressed concrete sleepers when the sleepers are deteriorated by excessive wears. Comparison between design codes of EUROCODE2 and AS2009-3600 will provide the insight into the durability of concrete sleepers. The outcome of the project will help rail track engineers to better design and maintain railway infrastructure, improving asset management efficacy.

## 2. Prediction for creep and shrinkage

### 2.1. Creep Prediction

The concrete under load that strain increases with time is due to creep. Therefore, creep can be defined as the increase in strain under the sustained stress and it can be several times as large as the initial strain [12]. If the load is removed, the strain decreases immediately due to elastic recovery and a gradual incomplete recovery due to creep. This behaviour is shown in Figure 3.



**Figure 3:** Time dependent creep

When creep is taken into account, its design effects are always evaluated under quasi-permanent combination of actions irrespective of the design situation considered, i.e. persistent, transient or accidental.

#### 2.1.1. Eurocode 2

The total creep strain  $\varepsilon_{cc}(\infty, t_0)$  of concrete due to the constant compressive stress of  $\sigma_c$  applied at the concrete age of  $t_0$  is given by :

$$\varepsilon_{cc}(\infty, t_0) = \varphi(\infty, t_0) \times \frac{\sigma_c}{E_c}$$

Where  $(\infty, t_0)$  is the final creep coefficient, which the value of  $\sigma_c$  does not exceed  $0.45f_{ck}(t_0)$ .  $E_c$  is the tangent modulus.

$$\varphi(\infty, t_0) = \varphi_{RH} \times \frac{16.8}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + t_0^{0.20})}$$

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}, \quad f_{cm} \leq 35MPa$$

$$\varphi_{RH} = (1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}} \alpha_1) \alpha_2, \quad f_{cm} > 35MPa$$

$$\alpha_1 = \left(\frac{35}{f_{cm}}\right)^{0.7}, \quad \alpha_2 = \left(\frac{35}{f_{cm}}\right)^{0.2} \quad f_{cm} = f_{ck} + 8MPa$$

$$t_0 = t_{0,T} \left( \frac{9}{2 + t_{0,T}^{1.2}} + 1 \right)^\alpha \geq 0.5,$$

$$\alpha = \{-1(S), 0(N), 1(R)\}$$

Where: RH = relative humidity in %,  $h_0 = 2Ac/u$  mm, Ac = cross sectional area, u = perimeter of the member in contact with the atmosphere, S, R and N refer to different classes of cement.

The final creep will be larger and final creep coefficient ( $\infty,0$ ) is multiplied by a factor  $k_\sigma$  if the compressive stress applied at the age of  $t_0$  exceeds  $0.45f_{ck}(t_0)$  as can happen during prestress transfer process. The Table 1 shows the value of  $k_\sigma$ . The factor  $k_\sigma$  is given by:

$$k_\sigma = \exp[1.5 \times \left( \frac{\sigma_c}{f_{ck}(t_0)} - 0.45 \right)]$$

**Table 1** Value of  $k_\sigma$  in terms of  $f_{ck}$

$\frac{\sigma_c}{f_{ck}(t_0)}$	$k_\sigma$
0.5	1.078
0.6	1.252
0.7	1.455
0.8	1.691
0.9	1.964
1.0	2.282

The creep coefficient at any age t can be given by empirical solutions [6, 10-12].

### 2.1.2. Australian Standard 3600-2009

The creep coefficient at any time  $\varphi_{cc}$  can be determined by:

$$\varphi_{cc} = k_2 k_3 k_4 k_5 \varphi_{cc,b}$$

Where  $k_2$  is the development of creep with time;  $k_3$  is the factor which depends on the age at first loading  $\tau$  (in days);  $k_4$  is the factor which accounts for the environment; and  $k_5$  is the factor which accounts for the reduced influence of both relative and humidity and specimen size.

For the development of creep with time  $k_2$  can be calculated by:

$$k_2 = \frac{\alpha_2 (t - \tau)^{0.8}}{(t - \tau)^{0.8} + 0.15 t_h}$$

$$\alpha_2 = 1.0 + 1.12 e^{-0.008 t_h}$$

$$t_h = 2A_g/u_e$$

Where  $t$  is any time in days;  $t_h$  is the hypothetical thickness;  $A_g$  is the cross-sectional area of the member;  $u_e$  is the portion of the section perimeter exposed to the atmosphere plus half the total perimeter of any voids contained within the section.

For factor  $k_3$  which depends on the age at first loading  $\tau$  can be shown as:

$$k_3 = \frac{2.7}{1 + \log(\tau)} \quad (\text{for } \tau > 1 \text{ day})$$

For the factor  $k_4$  which accounts for the environment:

$$\begin{aligned} k_4 &= 0.7 \text{ for an arid environment} \\ &= 0.65 \text{ for an interior environment} \\ &= 0.60 \text{ for a temperate environment} \\ &= 0.5 \text{ for a tropical or near-coastal environment} \end{aligned}$$

For the factor  $k_5$  is given by:

$$\begin{aligned} k_5 &= 1.0 \quad \text{when } f'_c \leq 50 \text{ MPa} \\ k_5 &= (2.0 - \alpha_3) - 0.02(1.0 - \alpha_3)f'_c \quad \text{when } 50 \text{ MPa} \leq f'_c \leq 100 \text{ MPa} \end{aligned}$$

Where  $\alpha_3 = 0.7 / (k_4 \alpha_2)$ . The basic creep coefficient  $\varphi_{cc,b}$  is shown table below:

$f'_c$ (MPa)	20	25	32	40	50	65	80	100
$\varphi_{cc,b}$	5.2	4.2	3.4	2.8	2.4	2.0	1.7	1.5

## 2.2. Shrinkage Prediction

Both of creep and shrinkage are influenced by the same parameters. Shrinkage is not an entirely reversible process like creep and it can be also influenced by relative humidity, surface exposed to atmosphere, compressive strength of concrete and types of cement. Shrinkage can be divided by two parts [13]:

- (1) Plastic shrinkage: it happens in few hours after concrete placed.
- (2) Dry shrinkage: evaporation leads to loss of water.

### 2.2.1. Eurocode 2

The total shrinkage strain  $\epsilon_{cs}$  can be given by:

$$\epsilon_{cs} = \epsilon_{ds} + \epsilon_{as}$$

Where  $\epsilon_{ds}$  is drying shrinkage strain; and  $\epsilon_{as}$  is autogenous shrinkage strain.

### 2.2.2. Australian Standard 3600-2009

The total shrinkage strain  $\epsilon_{cs}$  is shown below:

$$\epsilon_{cs} = \epsilon_{cse} + \epsilon_{csd}$$

Where  $\epsilon_{cse}$  is autogenous shrinkage strain;  $\epsilon_{csd}$  is drying shrinkage strain.

The autogenous shrinkage  $\epsilon_{cse}$  is given by:

$$\varepsilon_{cse} = \varepsilon'_{cse}(1.0 - \exp\{-0.1t\})$$

$$\varepsilon'_{cse} = (0.6f'_c - 1.0) \times 50 \times 10^{-6} \quad (f'_c \text{ in MPa})$$

$$\varepsilon_{csd,b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd,b}$$

Where  $\varepsilon'_{csd,b}$  depends on the quality of the local aggregates and may be taken as  $800 \times 10^{-6}$  for concrete supplied in Sydney and Brisbane,  $900 \times 10^{-6}$  in Melbourne and  $1000 \times 10^{-6}$  in elsewhere.

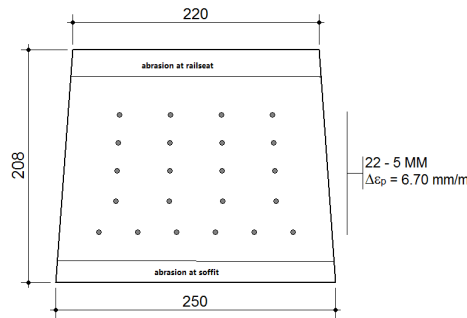
The drying shrinkage strain  $\varepsilon_{csd}$  after the beginning of drying ( $t - \tau_d$ ) can be estimated:

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd,b}$$

Where  $k_1$  is the factor which describes the development of drying shrinkage with time; and  $k_4$  is the factor which accounts for the environment [13-15].

### 3. Material Properties

The effects of various abrasions for estimating creep, shrinkage strain will be evaluated. The fundamental engineering properties of prestressed concrete sleeper used for calculation are based on previous research by Remennikov et al. [1]. The parametric results are generated for comparisons between Eurocode 2 (EC2) and Australian standard 3600-2009 (AS). Figure 4 shows the cross section at rail seat of the prestressed concrete sleepers.

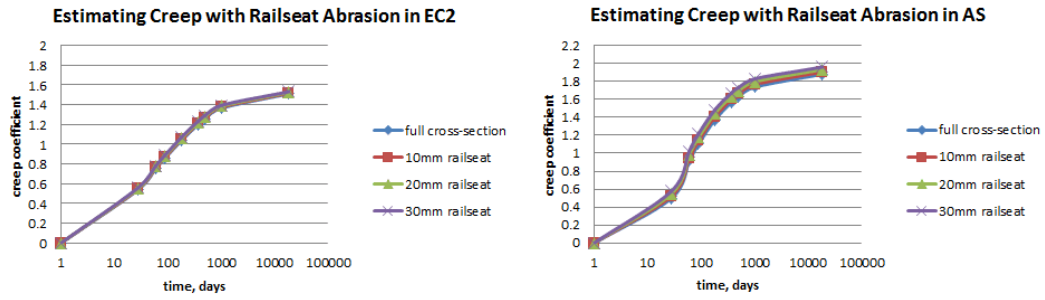


**Figure 4:** Cross section of railway sleepers

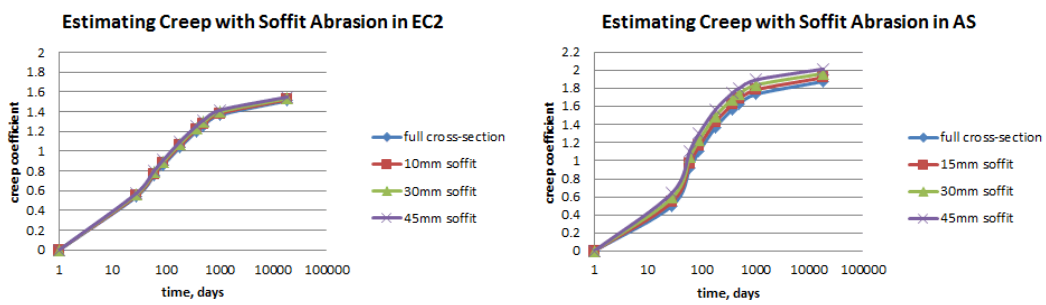
## 4. Results and discussions

### 4.1. Creep evaluations

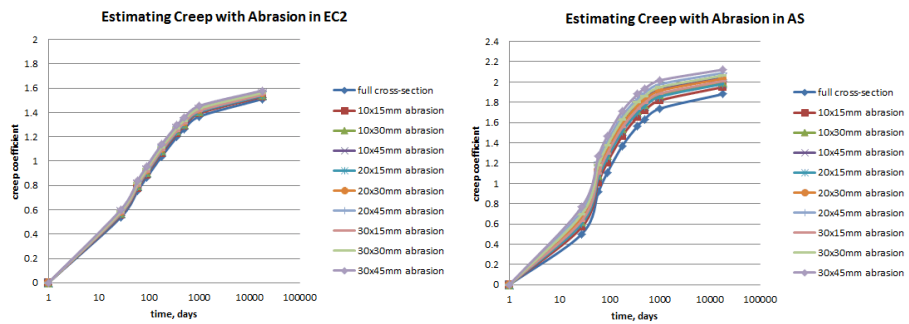
To investigate relationship between abrasion and creep, the 15 cases have been analysed in different abrasion (railseat 10, 20, 30mm, soffit 15, 30, 45mm and both of railseat and soffit abrasion), which are plotted in Figure 5. The data of creep coefficient are calculated by EC2 and AS codes respectively. All the cases are estimated from 1 day up to 18250 days (50 years) in the same conditions (uniform dimension of sleepers, 70% relative humidity, steam curing etc.).



(a) Railseat abrasion



(b) Soffit abrasion

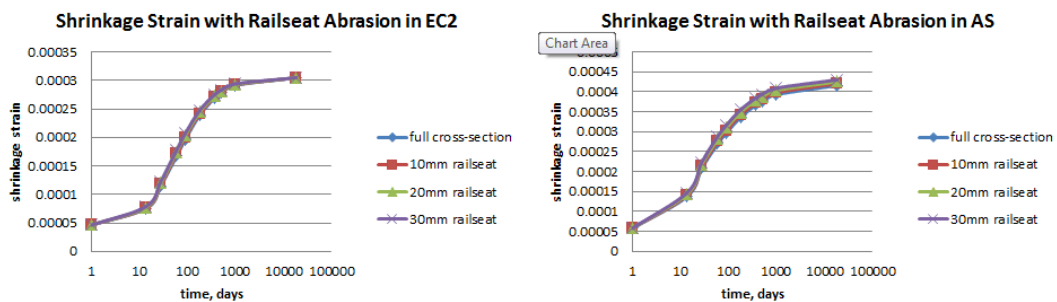


(c) Both of railseat and soffit abrasion

**Figure 5** Abrasion-creep effects

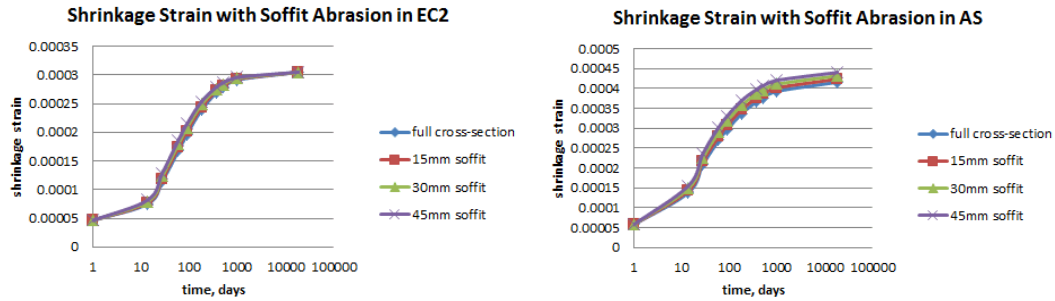
#### 4.2. Shrinkage evaluations

Figure 6 shows 15 cases of different abrasion on the shrinkage effect. The data of shrinkage stains are calculated by EC2 and AS3600-2009 codes respectively.

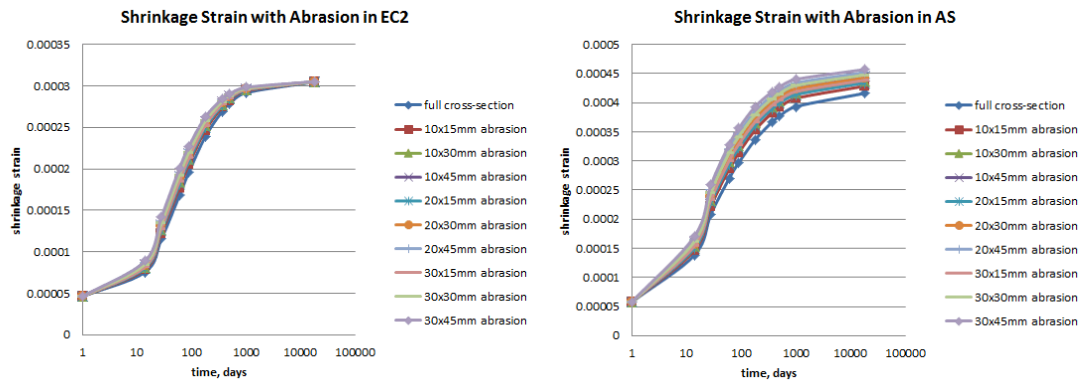




(d) Railseat abrasion



(e) Soffit abrasion



(f) Both of railseat and soffit abrasion

**Figure 6:** Abrasion-shrinkage effects

The results are based on parametric analysis and we found that creep and shrinkage in prestressed concrete sleeper can be significantly influenced by abrasion. Abrasion in the top of a sleeper (railseat) has less influence for both of creep and shrinkage than the bottom of a sleeper (soffit). Comparison full cross-section and 30mm abrasion on railseat of creep and shrinkage, the results are very close which just 1.41% and 0.05% respectively. However, the difference is up to 12.80% when abrasion happens in both of railseat and soffit.

## 5. Conclusions

There are two main duties for railway prestressed concrete sleepers (or railroad ties) that must successfully perform: first, to carry wheel loads from the rails to the ground; and second, to secure rail gauge for dynamic safe movements of trains. In many cases, an inappropriate design of the time-dependent behaviours of railway concrete sleepers due to their creep, shrinkage and elastic shortening responses of the materials affect significantly the rail gauge control. In addition, the concrete sleepers are often modified on construction sites to fit in other systems such as cables, signalling gears, drainage pipes, etc. This paper highlights constitutive models of concrete materials within the railway sleepers under different environmental conditions over time. The comparison has been carried out by a variety of reputable methods to evaluate shortening effects in railway prestressed concrete sleepers. Based on the sensitivity analyses, we found that creep and shrinkage in railway sleeper depend largely on the cross-section. According to the obtained data, the both of creep and shrinkage strains are

influenced by abrasion. This insight will improve the material design and structural restraints, which are very critical to the durability of railway track components.

### Acknowledgements

The authors would also like to thank British Department of Transport (DfT) for Transport - Technology Research Innovations Grant Scheme, Project No. RCS15/0233; and the BRIDGE Grant (provided by University of Birmingham and the University of Illinois at Urbana Champaign). The last author is gratefully acknowledge the Japan Society for the Promotion of Science (JSPS) for his JSPS Invitation Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the University of Tokyo, Tokyo, Japan. The authors are sincerely grateful to European Commission for the financial sponsorship of the H2020-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network,” which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing in extreme environments ([www.risen2rail.eu](http://www.risen2rail.eu)). We would also like to acknowledge the support from European Cooperation in Science and Technology (EU-COST) Action: TU1404 Towards the next generation of standards for service life of cement-based materials and structures.

### References

- [1] Kaewunruen. S et al, “Reliability-based conversion of a structural design code for railway prestressed concrete sleeper,” *Proc. IMechE.*, vol. 226, pp. 155 – 173, 2011.
- [2] Esveld C, “Modern Railway Track,” *The Netherlands MRT Press.*, 2001.
- [3] Taherinezhad. J et al, “A review of behaviour of prestressed concrete sleepers”, *Electronic Journal of Structural Engineering*, 13(1), 2013.
- [4] Kaewunruen. S et al, “Influence of surface abrasions on dynamic behaviours of railway concrete sleepers”, *International Congress on Sound and Vibrasiopn*, July 2017.
- [5] Kaewunruen S, Remennikov AM, Aikawa A. “A numerical study to evaluate dynamic responses of voided concrete railway sleepers to impact loading,” *Acoustics 2011: Breaking New Ground, Gold Coast, Australia*, 2-4 November 2011, (pp. 1-8). [URL <http://ro.uow.edu.au/engpapers/628/>]
- [6] Kaewunruen S, Remennikov AM. “An alternative rail pad tester for measuring dynamic properties of rail pads under large preloads,” *Experimental Mechanics*, 2008, 65: 55-64.
- [7] Vu, M., Kaewunruen, S., Attard, M., “Chapter 6 – Nonlinear 3D finite-element modeling for structural failure analysis of concrete sleepers/bearers at an urban turnout diamond, in Handbook of Materials Failure Analysis with Case Studies from the Chemicals,” *Concrete and Power Industries*, p.123-160, Elsevier, the Netherlands. 2016 <http://dx.doi.org/10.1016/B978-0-08-100116-5.00006-5>.
- [8] Wiest, M., Kassa, E., Daves, W., Nielsen, J. C. O. & Ossberger, H. “Assessment of methods for calculating contact pressure in wheel-rail/switch contact. *Wear*,” 265, 1439-1445, 2008.
- [9] Wolf, H.E., J.R. Edwards, M.S. Dersch and C.P.L. Barkan. “Flexural Analysis of Prestressed Concrete Monoblock Sleepers for Heavy-haul Applications: Methodologies and Sensitivity to Support Conditions.” *In: Proceedings of the 11th International Heavy Haul Association Conference, Perth, Australia*, June, 2015.
- [10] Kaewunruen S, Ishida, T and Remennikov, AM. “Impact analyses for negative flexural responses (hogging) in railway prestressed concrete sleepers.” *J. Phys.: Conf. Ser.* 744(1): 012101. 2016. <http://dx.doi.org/10.1088/1742-6596/744/1/012101>.
- [11] Gamage EK, Kaewunruen S, Remennikov AM, Ishida T. “Toughness of Railroad Concrete Crossties with Holes and Web Openings.” *Infrastructures*. 2, 3. 2017, doi:10.3390/infrastructures2010003.
- [12] Neville, A. “Properties of concrete.” third edn. *United Kingdom: Longman ELBS*.1979.

- [13] Bhatt P. "Prestressed concrete design to eurocodes," first edn., *Abington: Spon Press*. 2011.
- [14] British Standards Institution. "Eurocode 2 - design of concrete structures: Part 1 - general rules and rules for buildings." *London: British Standards Institution*. 1992.
- [15] Gilbert, R et al. "Design of prestressed concrete to AS3600-2009," second edn., *Boca Raton: CRC Press*. 2016.
- [16]
- [17] Remennikov, A & Kaewunruen, S, "Determination of dynamic properties of rail pads using instrumented hammer impact technique," *Acoustics Australia*, 2005, 33(2), 63-67.
- [18] Kaewunruen, S; Remennikov, A M, "Dynamic properties of railway track and its components: recent findings and future research direction," *Insight - Non-Destructive Testing and Condition Monitoring*, Volume 52, Number 1, 1 January 2010, pp. 20-22(3).
- [19] Kaewunruen, S. & Remennikov, A.M., "An Alternative Rail Pad Tester for Measuring Dynamic Properties of Rail Pads Under Large Preloads," *Exp Mech*, 48: 55. doi:10.1007/s11340-007-9059-3, 2008.
- [20] Kaewunruen, S. "Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction," *Case Studies in Nondestructive Testing and Evaluation*, 2014, Volume 1, April 2014, Pages 19-24.
- [21] Kaewunruen, S. & Remennikov, A.M., "Effect of a large asymmetrical wheel burden on flexural response and failure of railway concrete sleepers in track systems," 2008, *Engineering Failure Analysis*, Volume 15, Issue 8, December 2008, Pages 1065-1075.
- [22] Kaewunruen, S. & Remennikov, A.M., "Experimental simulation of the railway ballast by resilient materials and its verification by modal testing," 2008, *Experimental Techniques*, Volume 32, Issue 4, July 2008, Pages 29-35.
- [23] Remennikov, A.M., & Kaewunruen, S., "Experimental load rating of aged railway concrete sleepers," 2014, *Engineering Structures*, Volume 76, 1 October 2014, Pages 147-162
- [24] Li, D., Kaewunruen, S. and Robery, P. "Effects of creep and shrinkage in railway prestressed concrete sleepers." *United Kingdom: University of Birmingham*. 2016.